

METHOD AND APPARATUS FOR REDUCING COMBUSTION RESIDUES IN
EXHAUST GASES

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DESCRIPTION

5 The present invention generally relates to the field of reduction of environmental pollution, particularly air pollution caused by the emissions of apparatuses, such as internal-combustion engines and burners for heating systems, whose operation involves the combustion of fuels, for
10 example fossil fuels such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum, including natural gas, coal, wood and the like. In particular, the invention relates to a method, and a related apparatus, for reducing combustion residues, particularly harmful
15 pollutants, in exhaust gases.

The problem of environmental pollution is nowadays very felt by people and governments, and efforts are constantly made to devise solutions for reducing the impact on the environment of the various human activities.

20 In particular, air pollution caused by the emissions of apparatuses such as internal-combustion engines and burners for heating systems, whose operation involves the combustion of fuels, particularly fossil fuel, such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum,
25 including natural gas, and coal, has probably been the first aspect of the more general problem of environmental pollution to be recognized.

Although the problem of massive emissions of pollutants into the atmosphere started with the advent of the steam-power machine at the dawn of the industrial revolution, it has been the impressive growth of vehicles circulating in urban areas in the decades following the second world war that has brought the problem in foreground.

Thus, on the one side, measures restricting the vehicle circulation have been and still are adopted when the situation reaches a level of crisis. On the other side, and in parallel, under the pressure of governments and of the 5 public opinion, vehicle manufacturers and research institutes have started to devise solutions to the problem of emissions of harmful pollutants by internal-combustion engines.

For example, in the geographic area of the European 10 Union, maximum levels of tolerated vehicle emissions have been set by law, and a system of classification of vehicle engines based on the respective level of emission of pollutants has been introduced; in particular, as from January 2001, the previous standards known as EURO1 15 (introduced in 1987) and EURO2 have been replaced by the more stringent standard EURO3, which will be in turn replaced by the even more strict standard EURO4 as from January 2006. This classification imposes that vehicles falling in the lower classes are not allowed to circulate in 20 case restrictive measures are issued by governments or public administrations in consequence to the approaching of a crisis situation.

The main pollutants present in exhaust gases of internal-combustion engines, particularly of the Diesel 25 type, are carbon oxide (CO), carbon dioxide (CO₂), uncombusted hydrocarbons (HC), various nitrogen oxides (NO_x), and Particulate Matter (PM), in particular carbon particulate.

Similar substances are found in the exhaust gases of 30 heating implants and, more generally, of any apparatus whose operation involves the combustion of fuels, particularly fossil fuel.

Each one of the above mentioned substances is harmful

to human health for one or more reasons, causing cancer, lung disease and the like. Thus, it would be of paramount importance to reduce as far as possible, or possibly even eliminate, these substances from the exhaust gases.

5 In view of the state of the art outlined in the foregoing, it has therefore been an object of the present invention to provide an effective solution to the problem of pollution due to the emissions of internal combustion engines and, more generally, to the problem of environment 10 pollution due to the emissions of any apparatus whose operation involves the combustion of fuels, particularly but not limitatively fossil fuel, such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum, including natural gas, and coal, or even wood, and generally any fuel 15 that can be exploited in a combustion process.

The Applicant has found that harmful pollutants (gases, dust, particulate material, particularly carbon particulate) which are normally produced by apparatuses whose operation involves the combustion of fuel, particularly but not 20 limitatively fossil fuel, such as internal combustion engines and burners of heating systems of buildings, can be substantially reduced, not to say completely eliminated, if the exhaust gases are submitted to a treatment that involves a post-combustion of the exhaust gases, and particularly a 25 radiant post-combustion, ignited by submitting the exhaust gases to radiant energy, providing for a fast increase of the exhaust gases temperature to a value in a properly chosen temperature range.

For the purposes of the present description, by radiant 30 combustion there is intended a combustion process that is ignited by a heat source not involving the presence of a flame, but irradiating electromagnetic energy, particularly in the range of wavelengths from InfraRed (IR) to

UltraViolet (UV).

In other words, the Applicant has found that by submitting the exhaust gases to radiant energy in a suitably designed radiant reactor, wherein the gases are subjected to 5 a relatively fast increase of their temperature, up to a value in the properly chosen temperature range, a substantially perfect post-combustion is achieved, where, for the purposes of the present invention, by "perfect" there is meant a post-combustion that allows substantially 10 eliminating any harmful component or substance, such as CO, CO₂, HC, nitrogen oxides, PM, in particular carbon particulate, sulphur oxides, from the exhaust gases that are originated by the combustion of fuels.

According to a first aspect of the present invention, a 15 method for reducing pollutants in exhaust gases generated from the combustion of fossil fuel as set forth in the appended independent method claim 1 is thus provided.

Summarizing, the method comprises treating the exhaust gases before releasing them in the environment, by 20 performing a post-combustion process according to which the exhaust gases are submitted to radiant energy so as to increase a temperature thereof to a value sufficient to ignite self-combustion.

According to a second aspect of the present invention, 25 there is also provided an apparatus for reducing pollutants in exhaust gases generated from the combustion of fossil fuel, as set forth in the appended independent apparatus claim 16.

In brief, the apparatus comprises means for treating 30 the exhaust gases before releasing them in the environment, such treating means comprising a radiant combustion chamber wherein the exhaust gases are caused to pass through, so as to be submitted to radiant heat for increasing a temperature

thereof to a value sufficient to ignite self-combustion, thereby a post-combustion process of the exhaust gases is performed before releasing them in the environment.

These and other features and advantages of the present invention will be made apparent by the following detailed description of some embodiments thereof, provided merely by way of non-limitative examples, description that will be conducted making reference to the annexed drawings, wherein:

Figure 1 is a schematic diagram showing, partly in terms of functional blocks, an apparatus implementing a method according to an embodiment of the present invention;

Figure 2 shows in axonometric view a possible practical embodiment of the apparatus shown schematically in **Figure 1**;

Figure 3 schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a first embodiment of the present invention;

Figure 4 schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a second embodiment of the present invention;

Figure 5 schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a third embodiment of the present invention;

Figure 6 schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a fourth embodiment of the present invention;

Figure 7 schematically shows, in axonometric view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a fifth embodiment of the present invention;

Figure 8 schematically shows, in longitudinal cross-sectional view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a sixth embodiment of the present invention;

Figure 9 schematically shows, in longitudinal cross-

sectional view, a radiant combustion reactor of the apparatus of **Figure 1**, according to a seventh embodiment of the present invention;

5 **Figure 10** depicts quite schematically another type of radiant combustion reactor adapted to be used in the apparatus of **Figure 1**;

Figure 11 schematically shows, in axonometric view, a first possible implementation of the radiant combustion reactor of **Figure 10**, in an embodiment of the present 10 invention;

Figure 12 schematically shows, in axonometric view, a second possible implementation of the radiant combustion reactor of **Figure 10**, in another embodiment of the present invention;

15 **Figure 13** shows rather schematically, in axonometric view, a third possible implementation of the radiant combustion reactor of **Figure 10**, in still another embodiment of the present invention;

20 **Figures 14A, 14B and 14C** schematically shows, in axonometric view and in cross-section, a first possible implementation of a third type of radiant combustion reactor adapted to be used in the apparatus of **Figure 1**;

25 **Figure 15** schematically shows, in axonometric view, a second possible implementation of said third type of radiant combustion reactor; and

Figure 16 schematically shows, in axonometric view, a third possible implementation of the third type of radiant combustion reactor.

30 With reference to the drawings, in **Figure 1** a schematic diagram is provided showing, partly in terms of functional blocks, an apparatus implementing a pollutants-reduction method according to an embodiment of the present invention.

The pollutants-reduction apparatus, denoted globally as

100, is schematically depicted as placed downstream a block 105, representative of a generic apparatus of any type whose 5 operation involves the combustion of fuels, particularly fossil fuels such as hydrocarbon fuels or hydrocarbon containing fuels such as petroleum, including natural gas, coal, wood, and the like, generally any fuel adapted to be used in a combustion process; for example, the apparatus 105 may be an internal-combustion engine of a vehicle, particularly but not limitatively of the Diesel type, or a 10 burner of a heating system for buildings. Downstream the pollutants-reduction apparatus 100, a block 110 is provided, schematically representing an exhaust system of any conventional type, for example a simple muffler of a vehicle.

15 In greater detail, the pollutants-reduction apparatus 100 has an input manifold 115i, for receiving combustion exhaust gases from the apparatus 105; the received exhaust gases are treated by the apparatus 100 before being released in the environment; the pollutants-reduction apparatus 100 20 has an output manifold 115o for delivering treated exhaust gases to the exhaust system 110 (it is however observed that the exhaust system 110 might also not be provided for, and the treated exhaust gases be released directly into the environment).

25 The input manifold 115i leads the exhaust gases to be treated to a gases pre-heating chamber 120, where the exhaust gases, received from the apparatus 105 at a relatively low temperature, are submitted to a preliminary heating process. Considering for example the case of exhaust 30 gases from an internal combustion engine, particularly of the Diesel type, the temperature of the exhaust gases should in theory be around 400 - 450 °C; however, experimental trials conducted by the Applicant have revealed that the

exhaust gases temperature is normally lower, falling in the range from approximately 150 °C to approximately 300 °C. The preliminary heating process in the pre-heating chamber **120** brings the exhaust gases temperature to a suitably higher 5 value, preferably a value higher than 400 °C, for example a value in the range from approximately 400 °C to 700 °C and, preferably, from approximately 550 °C or 600 °C to approximately 700 °C.

In an embodiment of the present invention, the pre-10 heating chamber **120** comprises means adapted to submitting the incoming exhaust gases to a compression, thereby the gases temperature rises. In particular, the pre-heating chamber **120** may comprise means adapted to impart a suitable acceleration to the exhaust gases, and particularly one or 15 more among a fan (or an arrangement of fans), a turbine (or an arrangement of turbines), a turbocompressor; these elements are only schematically indicated in **Figure 1**, and identified therein by **121**. The acceleration imparted to the exhaust gases is preferably such that the gas temperature is 20 raised to approximately 500 °C - 600 °C.

Preferably, downstream the means **121** for accelerating the exhaust gases, a Venturi tube (schematically represented in **Figure 1** and identified therein as **123**) is provided, for further compressing the exhaust gases and thus causing a 25 further increase of the temperature thereof, for example up to a temperature of approximately 700 °C.

From the pre-heating chamber **120**, the pre-heated gases are conveyed to a radiant combustion reactor or radiant combustion chamber **125**, situated just downstream the Venturi tube **123**. 30

The radiant combustion chamber **125**, which will be described in greater detail later on, is a chamber with walls made of suitable material, which are heated by a heat

source to a prescribed temperature, thereby the chamber walls radiate electromagnetic energy within the chamber (in the way that approximate the black-body radiation). Within the radiant combustion chamber **125** the temperature of the 5 exhaust gases is raised further and rather quickly from the pre-heating temperature, for example the initial approximately 700 °C, to a temperature in the range from approximately 900 °C to approximately 1200 °C, preferably from approximately 900 °C to approximately 1100 °C, suitable 10 to determine a combustion (post-combustion) of the exhaust gases; more generally, the upper limit of the temperature of the exhaust gases is determined by the requirement that, at such a temperature, the creation of nitrogen oxides is not relevant; thus, the maximum temperature of the gases within 15 the combustion chamber **125** may reach 1300 - 1400 °C. The increase in temperature is achieved by radiant electromagnetic energy, particularly in the wavelength range from IR to UV, radiating from the walls of the radiant combustion chamber **125**.

20 By subjecting the exhaust gases to such a fast increase in temperature, the exhaust gases post-combustion process that is automatically ignited allows substantially reducing or even eliminating the harmful, uncombusted particulates present in the exhaust gases. In particular, in the exhaust 25 gases, typically being a mix of oxygen, uncombusted hydrocarbons, carbon particulate, self-combustion is automatically ignited, because the gaseous fluid in the chamber **125** travels in an environment at a temperature which is higher than the self-combustion temperature (the specific 30 value of which depend on the substances present in the exhaust gases), and the combustion is carried out exploiting the radiant energy irradiating from the walls of the chamber **125**. This substantially improves the efficiency of the

combustion of the carbon particulates, which is more difficult than that of hydrocarbons because the combustion time is related exponentially to the size and shape of the particle.

5 It is observed that by ensuring that the gas temperature in the radiant combustion chamber **125** is sufficiently high, in particular higher than approximately 450 °C, preferably in the range from approximately 900 °C to approximately 1200 °C, and more preferably from 10 approximately 900 °C to approximately 1100 °C, i.e. below the temperature at which nitride oxides start forming, nitride oxides already present in the exhaust gases are reduced. To this purposes, the post-combustion process of the exhaust gases may be combined with known reduction 15 processes, such as the Non-Selective Catalytic Reduction (NSCR) process, in presence of oxygen (by providing a suitable feed of oxygen to the radiant combustion chamber, or the Selective Catalytic Reduction (SCR) process, in presence of a noble catalyst (e.g., platinum), maintained at 20 high temperature by the flow of the exhaust gases. It is pointed out that the NSCR and the SCR processes may be exploited in alternative to one another, or in combination, depending in particular on the structure, e.g. on the geometry, of the radiant combustion chamber **125**.

25 It is also observed that, in the radiant combustion chamber **125**, the post-combustion of the exhaust gases takes place at a constant pressure.

In **Figure 1** the radiant combustion chamber **125** is shown very schematically and it is depicted as a substantially 30 "C"-shaped duct; it is pointed out that this is not to be intended as a limitation to the present invention; in the following of the present description, the radiant combustion chamber **125** will be described in greater detail, and several

possible embodiments thereof will be presented and discussed. In any case, the structure of the radiant combustion chamber **125**, particularly the geometry thereof, shall be such that it is ensured that the exhaust gases are 5 submitted to the radiating energy for a time sufficient to reach the desired temperature, for example a temperature in the above-mentioned temperature range, adapted to induce the post-combustion of the pollutants.

10 Optionally, a first filtering element **130a** is arranged along the radiant combustion chamber **125** (for example, the radiant combustion chamber **125** may be made up of two parts in cascade, and the filtering element **130a** may be arranged between the first and the second part).

15 Upon leaving the radiant combustion chamber **125**, the post-combusted exhaust gases are led to a second filtering element **130b**.

20 Each one or both of the filtering elements **130a** and **130b** may comprise active filters, particularly selective filters, preferably active nanofilters in ceramic/zeolite material, and are used for trapping residual dust and Particulate Material (hereinafter, shortly, PM) still present in the exhaust gases after the post-combustion process in the radiant combustion chamber **125**. In particular, the first filtering element **130a**, if provided, 25 allows trapping the residual, uncombusted dust and PM present in the exhaust gases after a first post-combustion phase, while the second filtering element **130b**, positioned at the output of the radiant combustion chamber **125**, serves for trapping the uncombusted dust and PM still remaining in 30 the exhaust gases after the post-combustion. Depending on the type of nanofilters adopted, the filtering elements may act both as hot catalysts, and as pure filters,

It is pointed out that the specific arrangement, the

number and the dimensions of the nanofilters making up the filtering elements **130a** and **130b** will depend on the specific type of apparatus **105** to which the pollutant-reduction apparatus **100** is intended to be associated with. However, as 5 a general rule, nanofilters resistant to high temperatures should be used.

It is also observed that more than one intermediate filtering element **130a** may be provided along the radiant combustion chamber.

10 Preferably, the filtering elements **130a** and **130b** are removable from the apparatus **100** and, even more preferably, they are also reconditionable or recyclable.

15 Optionally, means suitable to favor the exit of the post-combusted gases from the radiant combustion chamber **125** are provided, as shown in phantom and indicated by **127** in **Figure 1**; for example, such means may comprise another Venturi tube, or any other device capable of determining a depression downstream the chamber **125**.

20 After being passed through the second filtering element **130b**, the treated exhaust gases (substantially freed of the harmful pollutants) are led to a heat exchange arrangement **135**. In the heat exchange arrangement **135** the temperature of the treated exhaust gases is lowered from the approximately 900 °C - 1200 °C to values suitable to avoid thermal shocks, 25 such as a temperature value of approximately 100 °C - 150 °C.

30 Expediently, as schematically depicted in the drawing, the heat exchange arrangement **135** is arranged in such a way that at least part of the heat released by the treated exhaust gases is exploited for pre-heating the incoming gases to be treated in the pre-heating chamber **120**, thereby alleviating the burden of the exhaust gases acceleration means.

Preferably, the heat exchange arrangement **135** is made of materials resistant to high temperatures, particularly sodium, lithium, titanium, etc), and it may be of the molded metal type, of the liquid metal type, of the plate type, of the spiral type; in case the apparatus **100** is intended to be installed on a vehicle, the heat exchange arrangement shall have a suitably compact design.

From the heat exchange arrangement **135**, the treated exhaust gases, from which the harmful pollutants have been substantially eliminated, are led to the output manifold **1150**, and then to the exhaust system **110** (for example, the muffler of the vehicle).

A control unit **140** is provided in the apparatus **100** for controlling the operation of the various components thereof (as schematized by the dash-and-dot lines in the drawing). In particular, the control unit **140** comprises electronic control means, preferably programmable, particularly microprocessor-based control means, adapted to execute suitable microprograms for implementing a predefined control flow, and sensors, such as pressure sensors and temperature sensors for detecting the operating temperature in the different parts of the apparatus **100**, such as the pre-heating chamber **120**, the radiant combustion chamber **125**, the heat exchange arrangement **135**.

The specific controls operated by the control unit **140** depend largely on the structure of the radiant combustion chamber **125**, but in general the control unit **140** shall at least ensure that a correct temperature is maintained within the chamber **125**.

Figure 2 is an axonometric view of a possible practical implementation of the pollutant-reduction apparatus **100**, particularly adapted to the installation on a vehicle such as a car or a bus. The different parts of the apparatus

shown schematically in **Figure 1** and described in the foregoing are identified in **Figure 2** with the same reference numerals.

In the following of the present description, several 5 different embodiments of the radiant combustion chamber **125** will be presented, being however intended that the list of presented alternatives is not to be intended as exhaustive, and several other embodiments can be devised. It is in fact pointed out that the specific spatial configuration and 10 structure of the radiant combustion chamber **125** may depend on the specific application.

In the embodiment shown in axonometric view in **Figure 3**, the radiant combustion chamber **125** comprises a substantially "U"-shaped duct **300**, having a pair of tubes 15 (radiant tubes) **300a**, **300b**, particularly substantially rectilinear, joined to each other and in communication of fluid with one another, so as to define thereinside a path for the exhaust gases, wherein the exhaust gases to be treated, received from the pre-heating chamber **120**, are made 20 to flow. Heating means are associated with the "U"-shaped duct **300** for heating the radiant tubes, for example Joule-effect heaters and, more particularly, a pair of electric resistors **305a**, **305b**, each one associated with a respective one of the two radiant tubes **300a**, **300b** of the "U"-shaped 25 duct **300**; particularly, the two resistors **305a**, **305b** are a spiral resistors, each one wound around the respective rectilinear radiant tube **300a**, **300b** of the duct **300**. The resistors **305a**, **305b** are suitably dimensioned (for example, commercially available resistors of the type Kanthal AM or 30 Kanthal AF are suitable), and can be connected either in parallel or in series; an electrical supply (for example provided by the vehicle battery, schematically indicated in the drawing as **350**, or by an autonomous battery, or by the

vehicle alternator) is controlled by the control unit **140** (as schematized in the drawing by a switch **355**). When powered, the heat generated by the resistors by Joule effect heats the radiant tubes, bringing them to a suitable 5 temperature, thereby the tubes radiate electromagnetic energy thereinside.

In the embodiment shown in axonometric view in **Figure 4**, the radiant combustion chamber **125** comprises two substantially "U"-shaped ducts **401**, **402**, similar to the 10 single, substantially "U"-shaped duct **300** of the previous embodiment, having respective pairs of substantially rectilinear radiant tubes (only three of which, denoted **401a**, **402a**, **402b**, are visible in the drawing) joined to each other and run through in cascade by the exhaust gases. The 15 two "U"-shaped ducts **401**, **402** are associated with heating means, in the form of four electrical resistors (only three of which, denoted **405a**, **405c** and **405d**, are visible in the drawing) particularly spiral resistors that, similarly to the resistors **305a**, **305b** of the previous embodiment, are 20 each one associated with, and particularly wound around, a respective substantially rectilinear radiant tube **401a**, **401b**, **402a**, **402b** of the ducts **401**, **402**, so as to cause heating thereof when powered by the, e.g., battery **350**. The resistors can be connected in parallel, or in series, or 25 partly in parallel and partly in series.

The radiant combustion chamber **125** in the embodiment shown in **Figure 5** comprises instead a generically "W"-shaped arrangement **500** of substantially rectilinear radiant tubes **500a**, **500b**, **500c** and **500d**, connected in cascade one to 30 another so as to be all run through, in succession, by the flow of exhaust gases received from the pre-heating chamber **120**; similarly to the two previous embodiments, associated with each radiant tube is a respective electrical resistor

505a, 505b, 505c and 505d, particularly a spiral resistor wound around the tube, for heating the tube by Joule effect. For the sake of simplicity, the electrical supply of the resistors is not expressly shown in the drawing, but it is 5 clear to those skilled in the art that a connection to, e.g., the vehicle battery similar to those of the previous embodiments can be provided for.

The radiant combustion chamber 125 in the embodiment of Figure 6 comprises again a substantially "U"-shaped duct 600 10 through which the exhaust gases to be treated are made to flow. However, differently from the previous three embodiments, the heating means that are associated with the duct 600 are not formed by electrical resistors spirally wound around the substantially rectilinear tubes of the duct 15 600, being instead formed by at least one, preferably a pair of radiating panels 605a, 605b (one of which shown in phantom, for the sake of clarity of the drawing) preferably in close-packed arrangement, each one having embedded therein a respective, properly dimensioned electrical 20 resistor 607, preferably arranged according to a winding path; albeit not expressly shown, an electrical supply similar to those shown in the previous embodiments is provided for supplying the electrical resistors 607 embedded in the panels 605a, 605b. The duct 600 is thus sandwiched 25 between the two radiating panels 605a, 605b, and receives heat therefrom.

A still different embodiment of radiant combustion chamber 125 is the one depicted in Figure 7, wherein instead of having a duct for the exhaust gases formed by tubes, the 30 radiant combustion chamber 125 comprises a hollow box-shaped enclosure 700, for example having either generically rectangular or generically circular cross-section, with an inlet 700i for receiving the exhaust gases and an outlet

700o for delivering the exhaust gases. Within the enclosure 700, a plurality of baffles 710 are provided, arranged so as to define a suitably winding path 715 for the gases from the inlet 700i to the outlet 700o. The enclosure 700 is 5 sandwiched between a pair of radiating panels (only one of the two panels, denoted 705a is shown, for the sake of clarity) with embedded resistors 707, similar to the panels 605a, 605b of the previous embodiment.

Figures 8 and 9 show in longitudinal cross-section two 10 further possible embodiments of the radiant combustion chamber 125. In particular, in the embodiment of Figure 8 the radiant combustion chamber comprises a pair of coaxial ducts 800a and 800b; the inner duct 800a is hollow and communicates at an end thereof opposite to the end receiving 15 the exhaust gases from the pre-heating chamber with the outer duct 800b; the outer duct 800b is substantially an external lining of the inner duct 800a, and has thereinside baffles 805 defining a substantially helical path for the gases. A suitably dimensioned spiral electrical resistor 810 20 is wound around the outer duct 800b. Around the resistor 810, a thermally-insulating lining 815 is provided. The exhaust gases are received from the pre-heating chamber 120 and are fed to the inner duct 800a, through which the gases flows substantially rectilinearly; then, the gases pass into 25 the outer duct 805b, which is heated by the electrical resistor 810 and wherein the gases flows following a generically helical path, being thus heated to the desired, self-combustion ignition temperature.

It is observed that if, as in the schematic arrangement 30 of Figure 1, an intermediate filtering 130a is provided for, two coaxial ducts 800 can be used, one upstream and the other downstream the filtering element 130a. Similar reasoning applies also to the previous embodiments,

consisting of differently arranged radiant tubes.

In a slightly different way, in the embodiment of **Figure 9** an elongated, generically toroidal body **900**, having either generically circular or rectangular cross-section, 5 has thereinside a generically helical duct **903** for the gases. The toroidal body **900** is heated by two electric resistors, an inner resistor **910a** and an outer resistor **910b**, particularly spiral resistors; the inner resistor **910a** is inserted in the central cavity of the toroidal body, 10 while the outer resistor **910b** is externally wound around the toroidal body **900**; the two resistors are substantially coextensive to the toroidal body. The exhaust gases flow through the helical duct **903**, and are heated by both the inner and the outer resistors.

15 Clearly, in both the two latter embodiments a resistor supply arrangement should be provided for, for example similar to those described in connection with the first embodiments presented.

It is observed that the specific dimensions and the 20 material of the ducts (e.g. the radiant tubes) making up the radiant combustion chamber **125** depend on the specific application; suitable materials that can be used for realizing the radiant ducts are for example INCONEL (an alloy containing tungsten and manganese) and ceramic. 25 Radiant tubes are also commercially available.

It is observed that the resistor power supply, controlled by the control unit **140**, should preferably be controlled so as to track changes in operating conditions, particularly of the apparatus **105**. For example, in some 30 applications, such as in the case of vehicles, an increased flow of exhaust gases inside the radiant combustion chamber **125** in consequence of, e.g., an acceleration of the vehicle, will require a possibly fast adaptation of the power

delivered by the heating resistances, so as to maintain the temperature within the chamber **125** in the desired range.

In order to avoid dispersions of energy, the radiant combustion chamber **125** is preferably thermally insulated
5 (this has been schematically depicted in the embodiments of **Figures 8** and **9**: equivalent thermal insulation should preferably be provided also in the embodiments of **Figures 3** to **4**, albeit not expressly shown in the respective drawings), for example by means of refractory silicon-
10 ceramic materials, or other suitable materials.

The embodiments of radiant combustion chamber **125** described up to now, albeit differing from each other in spatial configuration, are all based on a common, similar heating principle, involving the use of electric resistances
15 as Joule-effect heaters.

Hereinbelow, some further embodiments of the radiant combustion chamber will be presented which are based on a different heating principle.

In detail, instead of using Joule-effect heaters and,
20 particularly, electrical resistors, one or more optical radiation source, particularly one or more lasers are exploited for triggering the radiant reactor, i.e. for heating the radiant combustion chamber to the desired temperature.

25 Lasers are more and more widely exploited in several applications, either in industry and in consumer products, thanks to the fact that the emitted optical radiation has is very homogenous and concentrated, and that they have a very fast response.

30 **Figure 10** shows schematically a radiant combustion chamber **125** of the type exploiting optical radiation, generated by a suitable source such as a laser, as a heater.

In detail, the radiant combustion chamber **125** comprises

a combustion reactor enclosure **1000**; the spatial configuration of the combustion reactor enclosure **1000** is not limitative to the present invention, depending for example on the specific application: thus, in **Figure 10** the combustion reactor **1000** is schematically depicted as generically elliptical. The combustion reactor **1000** has walls **1005** made of suitable material, for example INCONEL steel, a composite material having a ceramic matrix, or special alloys, adapted to radiate heat when properly heated, and receives thereinside the exhaust gases to be treated.

Outside of and around the combustion reactor **1000**, an arrangement of optical radiation reflecting/deflecting elements **1010** is provided, such as mirrors and/or optical prisms, schematically depicted in the drawing as the internal faces of walls of a box-shaped casing **1007** containing the combustion reactor **1000**.

The arrangement of optical radiation reflecting/deflecting elements **1010** reflects/deflects optical radiation **1015** which is generated by one or more optical radiation sources, particularly lasers, schematically indicated in the drawing at **1020**. It is observed that the number and the arrangement of the lasers **1020** is not limitative to the present invention, depending for example on the shape of the combustion reactor **1000**; in the drawing, just by way of example, four lasers **1020** are shown, each one located at a respective corner of the box **1007**; the lasers **1020** may be fixed or movable, for example they can be partially rotate and/or be angularly oriented.

The optical radiation emitted by the laser(s) **1020**, controlled by the control unit **140**, is reflected/deflected by the optical radiation reflecting/deflecting elements **1010**, and hits the external side of the walls of the

combustion reactor **1000**, causing a substantially uniform heating thereof. In this way, the walls of the combustion reactor are brought to the radiative temperature, i.e. to a temperature such that a sufficient electromagnetic energy is
5 radiated from the walls of the combustion reactor into the enclosure **1000**.

In the following, some possible practical embodiments of radiant combustion chamber **125** exploiting the optical-based heating mechanism, particularly the laser-based
10 heating, will be presented, being intended that such embodiments are mere examples.

In particular, in the embodiment schematically shown in **Figure 11** the radiant combustion chamber **125** comprises a radiant tube **1100**, of suitable material, arranged so as to
15 be traversed by the exhaust gases coming from the pre-heating chamber **120**. Outside the radiant tube **1100**, a light reflecting arrangement **1105** is provided, schematically depicted as an outer tube coaxial and coextensive to the radiant tube **1100** and having internal light-reflecting
20 walls. The light reflecting tube **1105** reflects the laser radiation **1110**, generated by a laser **1120**, onto the radiant tube **1100**, thereby causing the heating thereof to the required temperature. The laser **1120** is shown schematically
25 as moving along the axis of the radiant tube; for example, the laser **1120** may be mounted to a carriage. The laser **1120** might also be caused to revolve around the tube **1100**.

It is observed that in **Figure 11** (and in the following drawings) a supply of oxygen (O_2) and ammonia (NH_4) into the tube **1100**, i.e., into the radiant combustion chamber, is
30 schematically shown; this supply, which is optional and could as well be provided in any one of the radiant combustion chamber embodiments described in the foregoing, serves for enabling an NSCR process for reducing nitrogen

oxides during the post-combustion of the exhaust gases.

A slightly different arrangement is schematically depicted in **Figure 12**, wherein the radiant combustion chamber **125** comprises a lined radiant tube **1200** having an inner hollow body **1200a** surrounded by an outer hollow body **1200b**, and wherein the exhaust gases are made to pass in the space **1203** between the inner and the outer hollow bodies, whilst a laser **1220** is arranged inside the inner hollow body **1200a**, and the latter has reflecting walls adapted to reflect the laser radiation. Also in this case, the laser **1220** is schematically depicted as movable along and rotatable about the axis of the inner hollow body **1200a**.

Figure 13 shows quite schematically a still different embodiment of the radiant combustion chamber **125**, having a substantially spherical shape, within which the exhaust gases to be treated are conveyed. The laser(s) **1320** is arranged externally to the spherical reaction chamber, and is for example movable so as to hit different areas of the surface thereof; for example, the laser(s) is associated to moving means suitable to cause the laser to revolve around the reaction chamber, so that the laser radiation hits different points of the chamber external surface and causes a substantially uniform heating thereof.

The substantially spherical shape of the combustion chamber **125** in the embodiment of **Figure 13** allows achieving a high effectiveness in the heating of the exhaust gases conveyed thereinto. In fact, the incoming exhaust gases, at a lower temperature, force the gases already undergone to the post-combustion process to leave the reaction chamber. Also, albeit not shown in the drawing, an optical radiation reflecting/deflecting arrangement may also in this case be provided for.

It is observed that by properly disaligning the inlet

and the outlet of the gases into/from the reaction chamber, a vortex can be created inside the reaction chamber that, proximate to the chamber outlet, optimizes the gas recirculation, favoring the exit of the portion at a higher 5 temperature. This is further helped by the Venturi accelerator **127** that may be placed at the exit of the chamber.

The use of one or more lasers for heating the radiant combustion chamber has the advantage of allowing a 10 substantial reduction in the dimensions of the combustion reactor, because when turned on the laser(s) cause the reactor walls to almost instantly reach the desired operating temperature (necessary for inducing self-combustion of the exhaust gases), and, similarly, the 15 laser(s) can be turned off almost instantaneously.

A suitable number of sensors may be associated with the walls of the radiant combustion chamber so as to enable the control unit **140** causing the laser radiation to hit the desired areas of the radiant combustion chamber walls, 20 scanning the surface according to prescribed patterns in such a way as to cause the surface be homogeneously hit.

In particular, a specific control software may be executed by the control unit **140**, according to which the surface to be hit by the laser radiation is subdivided 25 according to several different parameters, such as the temperature of the areas already hit by the radiation, the difference in temperature between these areas and those not yet hit (the cold areas), the target temperature. A dynamic temperature map is thus built, and such a map, in addition 30 to being used by the control unit to control the laser, might also be displayed, on suitable display devices, to an operator, so as to enable constantly control the operation of the apparatus.

The control software may be based on variation calculations or on perturbation calculation, or on a simpler "fork shoot" (a term derived from the navy jargon and indicating a successive approximation process).

5 Moreover, the use of laser(s) allows a better controllability of the whole post-combustion process. In fact, by properly driving the pulsed laser(s) through the suitably programmed control unit, the post-combustion process of the exhaust gases can be controlled finely in
10 dependence of the density of the exhaust gases and their velocity, which in turn depend on the engine's RPMs and on the engine operating temperature.

15 Additionally, the use of laser(s) reduces the energy consumption, because only relatively high peak energies are required.

The use of lasers thus allows reducing the operation costs.

Those skilled in the art will readily understand that the lasers used, and their optical power, may vary depending
20 on contingent needs, according to the specific applications. The laser(s) may be operated in Continuous Wave (CW) mode or, preferably, in pulsed mode. also, the laser(s) may be of rotating type, or a laser(s) emitting multiple beams properly out-of-phase.

25 The embodiments shown schematically in **Figures 14A, 14B and 14C**, in **Figure 15** and in **Figure 16** relates to radiant combustion chambers within which movable means are provided for propelling the gases during the post-combustion process and/or for varying the internal geometry of the radiant
30 combustion chamber during operation. It is pointed out that these, and other equivalent solutions, may be adopted in either a Joule-effect heated reaction chamber, or in a radiant combustion chamber heated by optical radiation, and

in general in any type of radiant combustion chamber, irrespective of the heating means.

In particular, in **Figures 14A, 14B** and **14C** there is schematically shown, in axonometric and cross-sectional views, a substantially cylindrical radiant combustion chamber **1400** (depicted as transparent, for the sake of clarity) with a tri-lobes rotor **1405** rotatably inserted therein, having lobes **1405a, 1405b, 1405c** angularly spaced of approximately 120° from each other, and with different possible cross-sectional areas, as visible in the cross-sectional views of **Figures 14B** and **14C**.

A suitable drive arrangement is also provided, not shown in the drawings, for causing the rotor **1405** to rotate about its axis inside the chamber.

If, for example, a laser source is used for heating the radiant combustion chamber, as in the embodiment of **Figure 11** the laser radiation hits the chamber from the outside thereof. Alternatively, the radiant combustion chamber **1400** may be a radiant tube similar to the radiant tubes of the embodiments of **Figures 3 to 6**, and in this case the heating means may comprise a spiral electrical resistor wound around the chamber **1400**, or one or two heat radiating panels with electrical resistors embedded therein.

The exhaust gases to be treated are conveyed into the chamber through an inlet **1410i**; within the radiant combustion chamber, the rotation of the rotor **1405** causes a dynamic partition of the internal space of the chamber into three dynamically-varying portions, and facilitates the flow of the gases towards an outlet **1410o** or **1400o'**; while flowing from the inlet to the outlet, the gases undergoes a post-combustion process due to the radiant energy radiating from the walls of the chamber **1400**.

It is observed that the inlet **1410i** and the outlet

1410° or 1400° to/from the radiant combustion chamber can either be axially aligned or not, and either the inlet or the outlet 1410° or 1400° or both may even be perpendicular to the chamber axis. As mentioned in the foregoing, **Figures 5 14B and 14C** show possible different shapes of the rotor 1405, differing from each other for the cross-sectional area. Other shapes are clearly possible.

In the embodiment of **Figure 15**, a rotor 1505 constituted by an endless screw is rotatably arranged within 10 the cylindrical radiant combustion chamber 1400 (depicted again as transparent, for clarity); a suitable drive arrangement, not shown in the drawing, is provided for rotating the rotor 1505. Also in this case, the cross-sectional shape of the rotor can vary so as to vary the 15 internal volume of the post-combustion chamber, in dependence of the specific application.

Finally, in the embodiment of **Figure 16** a spherical reaction chamber 1600 is provided (shown in the drawing in sectional view along a diametral plane), instead of a 20 cylindrical one, and an internal rotor 1605 is rotatably arranged within the spherical reaction chamber 1600. The rotor 1605 has a generically spherical shape, with three substantially hemispherical depressions 1605a, 1605b and 1605c, the rotor 1605 is thus shaped so as to define three 25 post-combustion chambers within the chamber 1600, of suitable volumes.

As already pointed out, the embodiments shown in **Figures 14A, 14B, 14C, 15 and 16** do not necessarily require the use of a laser(s) as a heating means, being possible to 30 exploit them in connection with more conventional heating means, such as Joule-effect heaters (electric resistors). However, when used in association with a laser, the proper control of the motion of the rotors may optimize the

efficiency of the laser pulses.

The Applicant has found that thanks to the method and apparatus of the present invention, approximately 90% of the carbon monoxide, carbon particulate, uncombusted hydrocarbon (C_xH_y) are eliminated from the exhaust gases, and nitrogen oxides (NO_x) are reduced of almost 90%.

The method and apparatus according to the present invention find application in any system wherein combustion of fuels is provided for, such as for example internal-
10 combustion engines, using Diesel fuel, gasoline, methanol, mix of alcohols, natural gas, LPG, Kerosene, fuel oil, hydrocarbons mixed with water, GECAM, BLUDIESEL, fuel for planes with additives, masut for marine engines.

It is observed that the post-combustion process carried
15 out in the radiant combustion chamber may be either continuous, partially continuous or discontinuous (intermittent). By continuous there is intended a process wherein there is no substantial separation between the incoming, relatively cold exhaust gases to be treated and
20 the outgoing, hot and already treated exhaust gases: the cold phase is contiguous to the hot phase. A partially continuous post-combustion process is one in which there is a certain separation in time (for example, of the order of 10⁶ seconds) between the cold and the hot phases, i.e.
25 between the cold and the hot gases; this is for example the case where a combustion chamber such as those of the embodiments of **Figures 14A, 14b, 14c, 15 and 16** is used, wherein the provision of the internal rotor allows for a certain separation of the cold gases from the hot gases. A
30 discontinuous or intermittent post-combustion process is instead one in which the post-combustion chamber is loaded with gases, then the chamber is closed, the post-combustion process is carried out, the chamber is opened to discharge

the treated gases, and then the process is re-started.

It is pointed out that the method and apparatus according to the present invention can be used in conjunction with other known pollutants-reduction methods and apparatuses, particularly those directed to eliminating nitrogen oxides (NO_x), such as Ignition Time Retardation (ITR), advanced systems of reactant injection, such as the RJM Aris™ technology, water injection, emulsions, turbocompressed air, air mixed to a fuel, Exhaust Gas Recirculation (EGR) systems, introduction of refrigerated air, high injection pressure and change of air/fuel proportion, a turbo composite, and the like. In particular, all these known techniques are preferably implemented downstream the apparatus of the present invention.

The method and apparatus of the present invention can also be used in conjunction with the known devices for eliminating sulphur oxides, particularly sulphur dioxide (SO₂) and sulphuric oxide (SO₃).

The apparatus according to the present invention can take the form of a kit ready to be installed on a vehicle, as a retrofit

The method and apparatus according to the present invention are capable of reducing substantially the emissions of vehicles propelled by internal-combustion engines, and also hybrid-propulsion vehicles, with both electrical and internal-combustion propulsion, will greatly benefit of the apparatus.

Although the present invention has been disclosed and described by way of some embodiments, it is apparent to those skilled in the art that several modifications to the described embodiments, as well as other embodiments of the present invention are possible without departing from the scope thereof as defined in the appended claims.

For example, other types of radiant combustion chamber might be exploited, particularly radiant combustion chambers provided with different heating means, such as gas burners.

CLAIMS

1. A method for reducing combustion residues in exhaust gases generated from the combustion of a fuel, comprising
5 treating the exhaust gases before releasing them in the environment,

characterized in that

10 said treating the exhaust gases comprises performing a post-combustion process by submitting the exhaust gases to radiant energy in a radiant combustion reactor (125), so as to increase a temperature of the exhaust gases to a value sufficient to cause self-combustion.

15 2. The method according to claim 1, in which within the radiant combustion reactor the temperature of the exhaust gases is increased to a value in the range from approximately 400 °C to approximately 1400 °C, preferably from approximately 900 °C to approximately 1200 °C and, even more preferably, from approximately 900 °C to approximately
20 1100 °C.

25 3. The method according to claim 1 or 2, further comprising submitting the exhaust gases to filtering (130a, 130b) so as to substantially eliminate residual uncombusted dust and particulate material present in the exhaust gases, said filtering being performed at least after the post-combustion.

30 4. The method according to claim 3, in which said post-combustion process is carried out in at least two stages, the method comprising submitting the exhaust gases to said filtering also between the two stages.

5. The method according to claim 3 or 4, in which said filtering is an active filtering.

6. The method according to any one of the preceding 5 claims, further comprising pre-heating (120) the exhaust gases before performing the post-combustion process.

7. The method according to claim 6 when depending on 10 claim 2, in which said pre-heating the exhaust gases comprises bringing a temperature of the exhaust gases over approximately 400 °C, preferably in the range from approximately 400 °C to approximately 700 °C.

8. The method according to claim 7, in which said pre- 15 heating the exhaust gases comprises accelerating and compressing (123,121) the exhaust gases.

9. The method according to any one of the preceding 20 claims, further comprising lowering a temperature (135) of the exhaust gases after performing the post-combustion process before releasing the post-combusted exhaust gases in the environment.

10. The method according to claim 9, in which the 25 temperature of the post-combusted exhaust gases is lowered to a value in the range from approximately 100 °C to approximately 150 °C.

11. The method according to claim 9 or 10 as depending 30 on claim 3, in which said lowering the temperature of the post-combusted exhaust gases is performed after said filtering.

12. The method according to any one of claims 9, 10 or 11 as depending on claim 6, in which said lowering the temperature of the exhaust gases comprises exploiting a heat released by the post-combusted exhaust gases for pre-heating 5 of the exhaust gases to be post-combusted.

13. The method according to any one of the preceding claims, in which the post-combustion process is carried out continuously, with the exhaust gases to be submitted to 10 post-combustion being in substantially contiguity relationship with the post-combusted exhaust gases within the radiant combustion reactor.

14. The method according to any one of claims 1 to 12, 15 in which the post-combustion process is carried out partially continuously, with the exhaust gases to be submitted to post-combustion being separated from the post-combusted exhaust gases within the radiant combustion reactor of a time of the order of 10^6 seconds.

20

15. The method according to any one of claims 1 to 12, in which the post-combustion process is carried out discontinuously, with the exhaust gases already submitted to post-combustion being kept substantially separated from the 25 exhaust gases to be submitted to post-combustion.

16. An apparatus (100) for reducing combustion residues, particularly pollutants, in exhaust gases generated from the combustion of a fuel, comprising means 30 for treating the exhaust gases before releasing them in the environment,

characterized in that
said treating means comprise a radiant combustion

reactor (125) wherein the exhaust gases are caused to pass through, so as to be submitted to radiant energy for increasing a temperature of the exhaust gases to a value sufficient to cause self-combustion, thereby a post-
5 combustion process of the exhaust gases is performed before releasing them in the environment.

17. The apparatus according to claim 16, in which within the radiant combustion reactor the temperature of the
10 exhaust gases is increased to a value in the range from approximately 400 °C to approximately 1400 °C, preferably from approximately 900 °C to approximately 1200 °C, more preferably from approximately 900 °C to approximately 1100 °C.

15

18. The apparatus according to claim 16 or 17, further comprising filtering means (130a, 130b) adapted to substantially eliminate residual uncombusted dust and particulate material present in the exhaust gases, said
20 filtering means (130b) being arranged at least downstream the radiant combustion reactor.

19. The apparatus according to claim 18, in which said radiant combustion reactor comprises at least two chambers,
25 one downstream the other, the filtering means (130a) being additionally arranged between the two chambers.

20. The apparatus according to claim 18 or 19, in which the filtering means comprise active filters, particularly
30 selective filters based on ceramic and zeolite materials.

21. The apparatus according to any one of claims 16 to 20, further comprising a pre-heating chamber (120), upstream

the radiant combustion reactor, for pre-heating the exhaust gases before performing the post-combustion process.

22. The apparatus according to claim 21 when depending
5 on claim 17, in which in said pre-heating chamber the exhaust gases are pre-heated to a temperature over approximately 400 °C, preferably in the range from approximately 400 °C to approximately 700 °C.

10 23. The apparatus according to claim 21, in which said pre-heating chamber includes means (121) for accelerating and compressing the exhaust gases, particularly one or more among a fan or an arrangement of fans, a turbine, a turbocompressor.

15

24. The apparatus according to claim 23, in which said pre-heating chamber further comprises a Venturi tube (123) for further accelerating the exhaust gases.

20 25. The apparatus according to any one of claims 16 to 24, further comprising a heat-exchange arrangement (135) downstream the radiant combustion reactor, for lowering a temperature of the exhaust gases after performing the post-combustion process before releasing the post-combusted
25 exhaust gases in the environment.

26. The apparatus according to claim 25, in which the heat-exchange arrangement is adapted to lowering the temperature of the post-combusted exhaust gases to a value
30 in the range from approximately 100 °C to approximately 150 °C.

27. The apparatus according to claim 25 or 26 as

depending on claim 18, in which said heat-exchange arrangement is placed downstream said filtering means.

28. The apparatus according to any one of claims 25, 26
5 or 27 as depending on claim 21, in which said heat-exchange arrangement is operatively coupled to the pre-heating chamber, so that a heat released by the post-combusted exhaust gases in the heat-exchange arrangement is exploited for the pre-heating the exhaust gases in the pre-heating
10 chamber.

29. The apparatus according to any one of claims 16 to 28, further comprising a control unit (140), particularly an electronic, programmable control unit, for controlling the
15 post-combustion process.

30. The apparatus according to any one of claims 16 to 29, in which the radiant combustion chamber comprises an enclosed path for the exhaust gases, and heating means
20 associated with the enclosed path for heating walls thereof.

31. The apparatus according to claim 30, in which said heating means comprise Joule-effect heaters
(305a, 305b; 405a, 405c, 405d; 505a-d; 607; 707; 810; 910a, b).

25

32. The apparatus according to claim 31, in which said enclosed path comprises an arrangement of ducts
(300; 400; 500; 600; 700; 800) comprising at least one duct for the passage of the exhaust gases, and having associated
30 therewith electrical resistors for heating the duct walls.

33. The apparatus according to claim 32, in which said arrangement of ducts comprises at least one among a

substantially "U"-shaped (300), a substantially double "U"-shaped (400) or a substantially "W"-shaped (500) arrangement of ducts, at least one of said ducts having wound around it at least one spiral resistor controllably powered for 5 heating the duct walls.

34. The apparatus according to claim 31, comprising an arrangement of ducts associated with at least one heat radiating panel (605a,605b;705a), having embedded therewith 10 a Joule-effect heat generator (607;707).

35. The apparatus according to claim 30, in which said heating means comprises an optical radiation source (1020;1120;1220;1320), particularly a laser.

15

36. The apparatus according to claim 35, in which said optical radiation source comprises at least one laser.

37. The apparatus according to claim 36, in which said 20 at least one laser is operated in pulsed mode.

38. The apparatus according to claim 36 or 37, further comprising optical radiation reflecting/deflecting means (1007;1105;1200a) for reflecting/deflecting the optical 25 radiation onto the enclosed path.

39. The apparatus according to any one of claims 16 to 38, in which means (1405;1505;1605) are provided within the radiant combustion reactor for determining a separation of 30 different parts of the exhaust gases undergoing different phases of the post-combustion process.

40. The apparatus according to claim 39, in which said

means comprise a rotor rotatably arranged inside the radiant combustion reactor.

41. A system comprising a fuel combustion apparatus
5 (105) in which a combustion process of a fuel takes place,
and an apparatus (100) for treating exhaust gases
originating from the combustion process, wherein said
apparatus for treating the exhaust gases is realized
according to any one of the claims 16 to 40.

10

42. The system according to claim 41, in which said
fuel combustion apparatus is an internal combustion engine,
particularly a vehicle engine.

15

43. The system according to claim 41, in which said
fuel combustion apparatus is a burner of a heating system.

METHOD AND APPARATUS FOR REDUCING COMBUSTION RESIDUES IN
EXHAUST GASES

* * * * *

ABSTRACT

5

A method and an apparatus for reducing combustion residues, particularly pollutants, in exhaust gases generated from the combustion of fuels such as fossil fuels, wood and the like. The exhaust gases are treated before 10 releasing them in the environment. Said treating of the exhaust gases comprises performing a post-combustion process by submitting the exhaust gases to radiant heat so as to increase a temperature of the exhaust gases to a value sufficient to cause self-combustion.

15

(Figure 1)

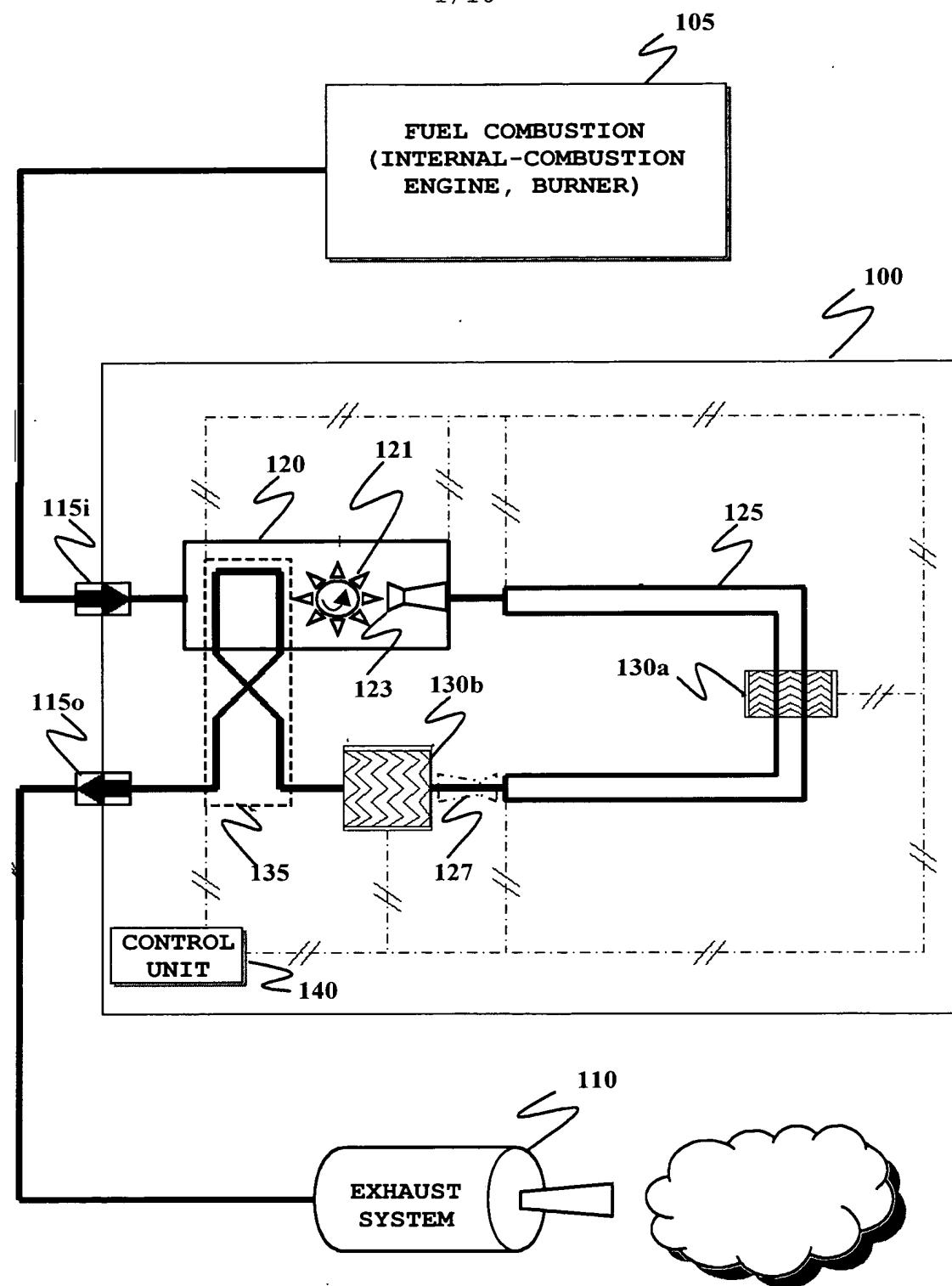


FIG. 1

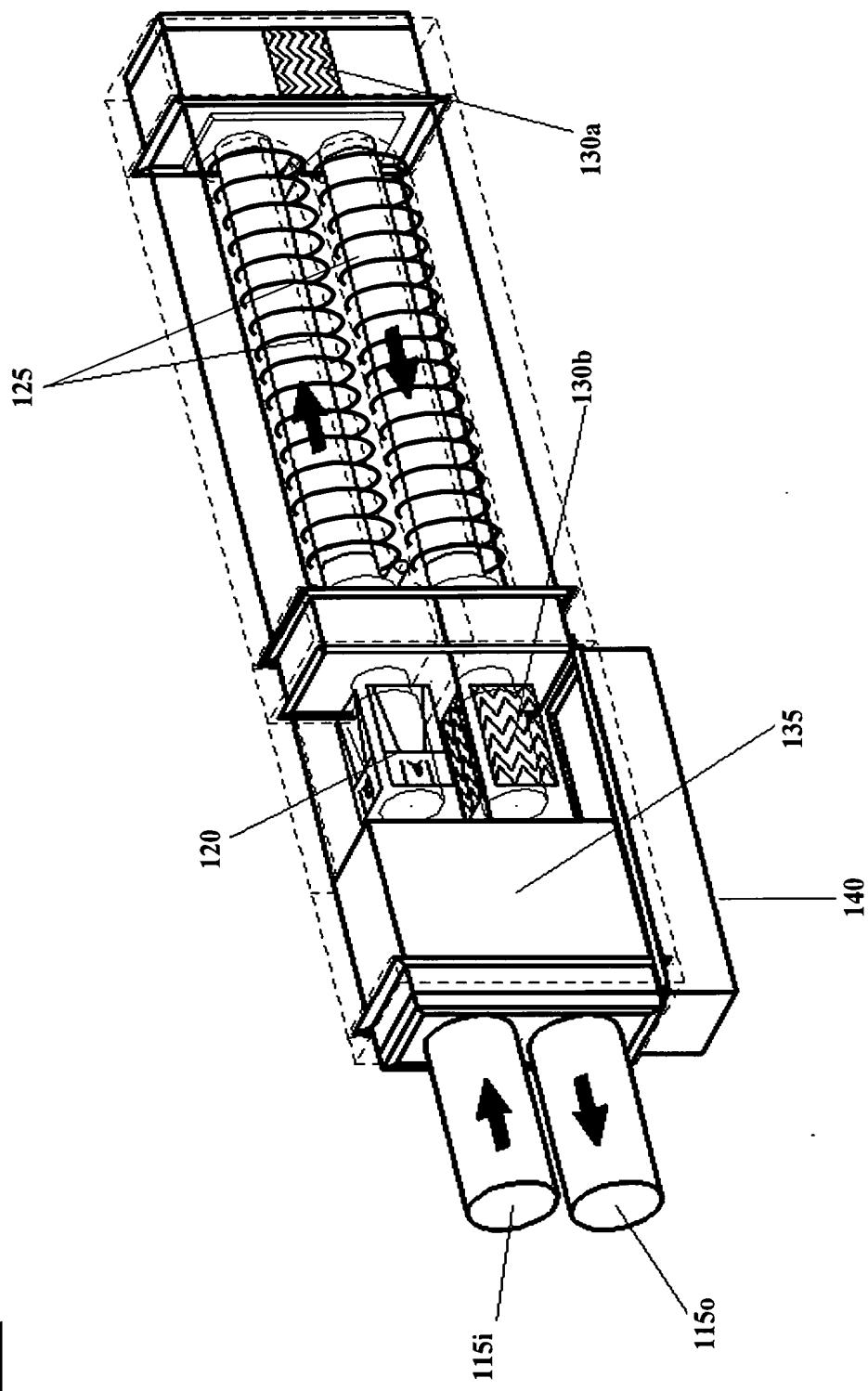
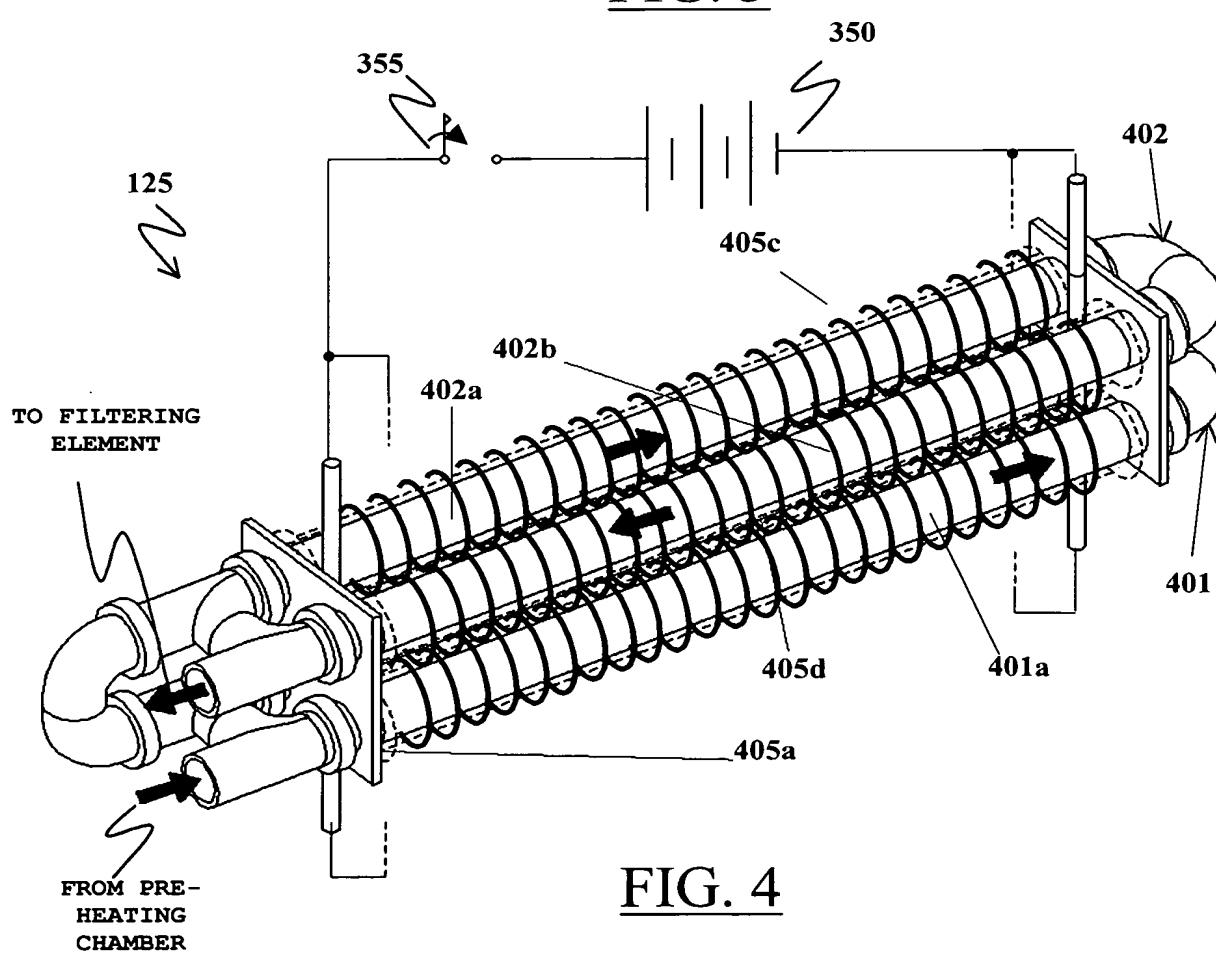
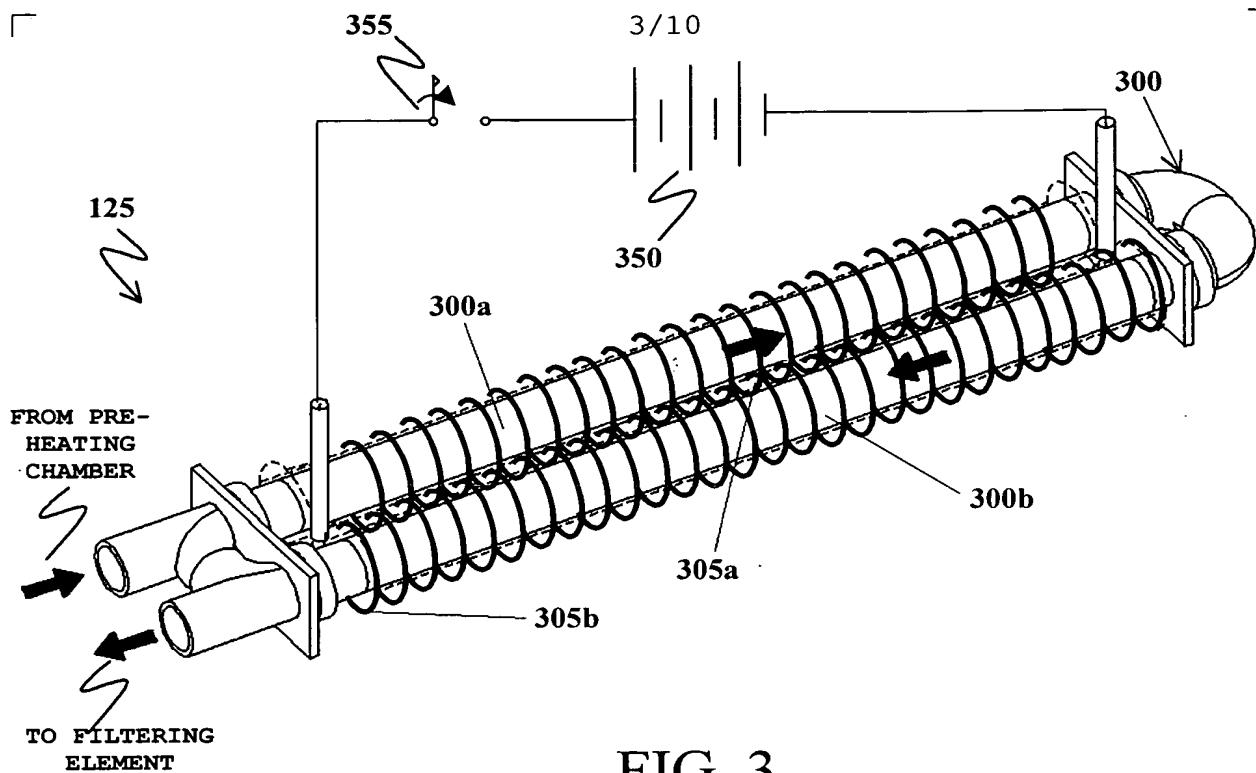


FIG. 2



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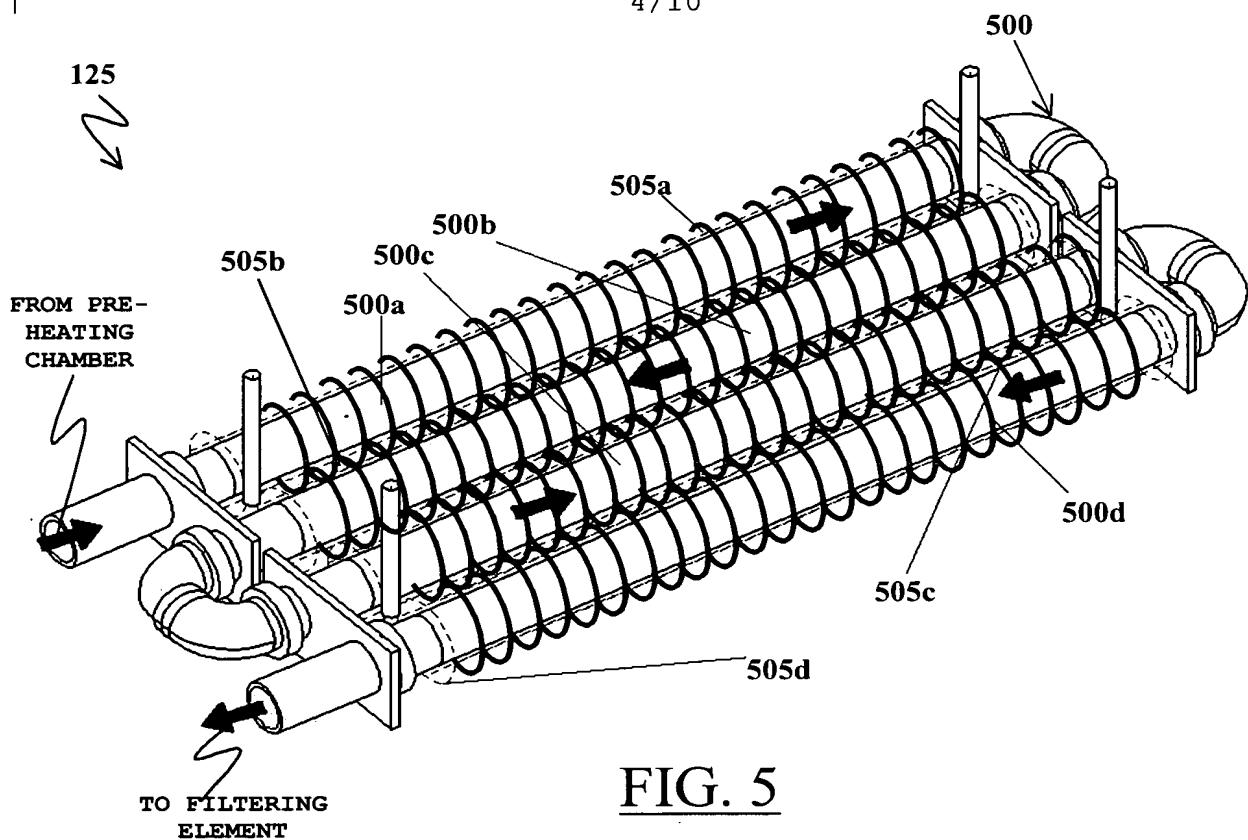


FIG. 5

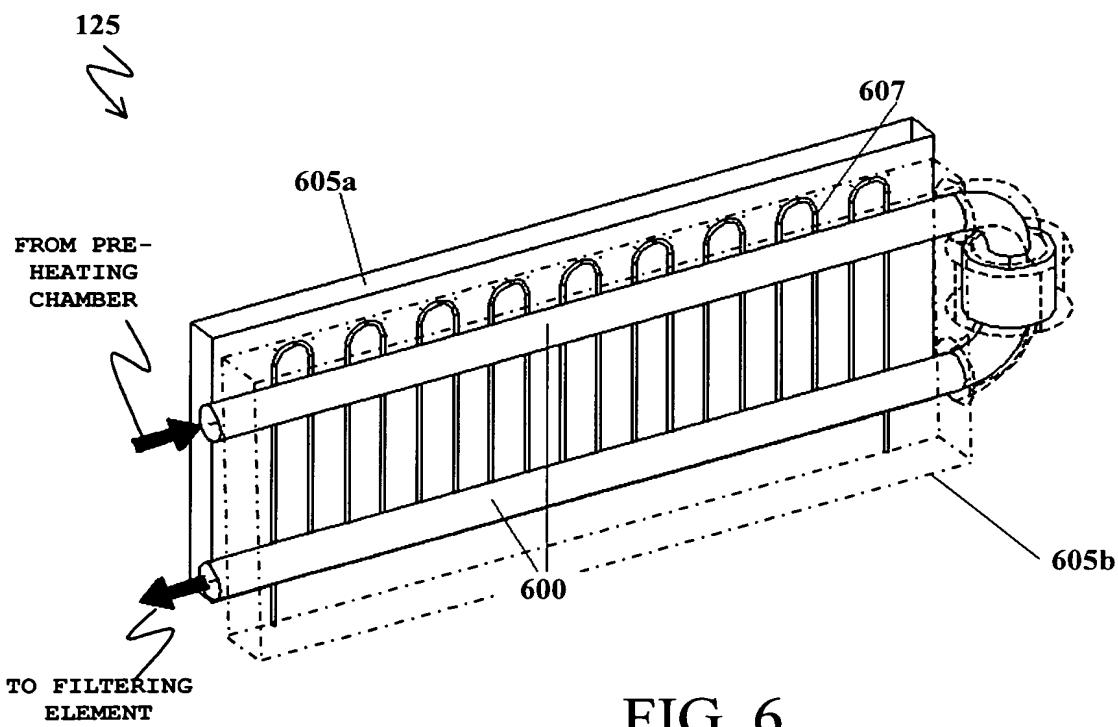


FIG. 6

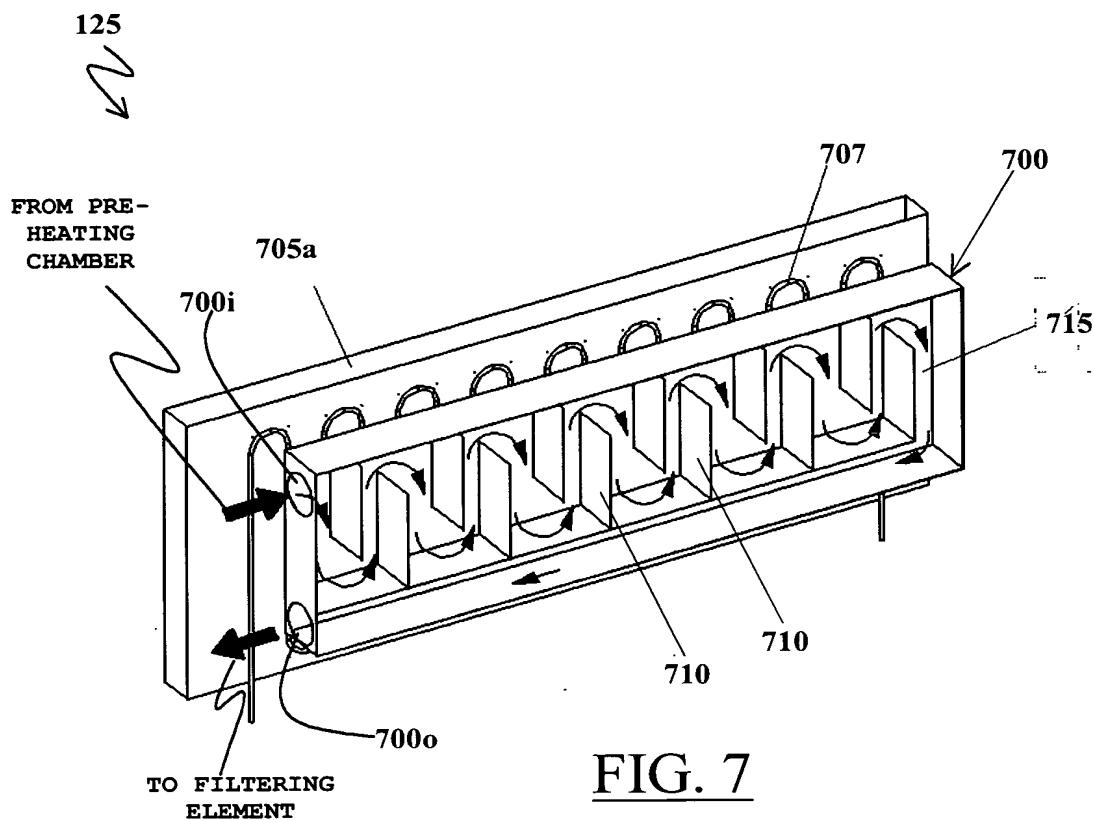


FIG. 7

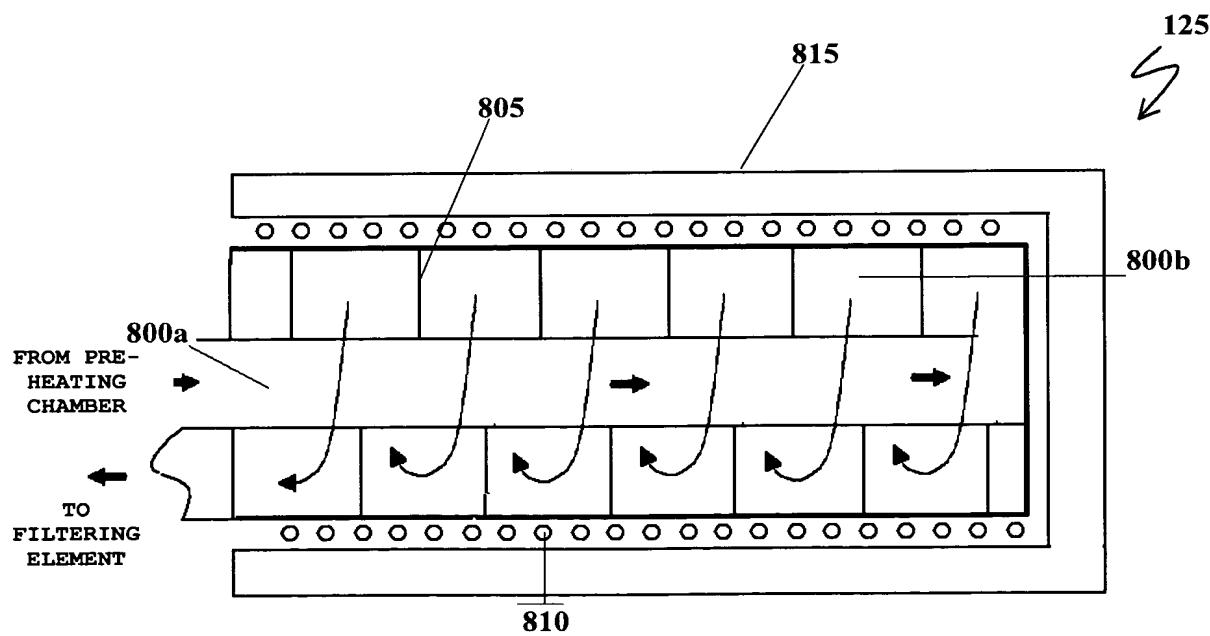


FIG. 8

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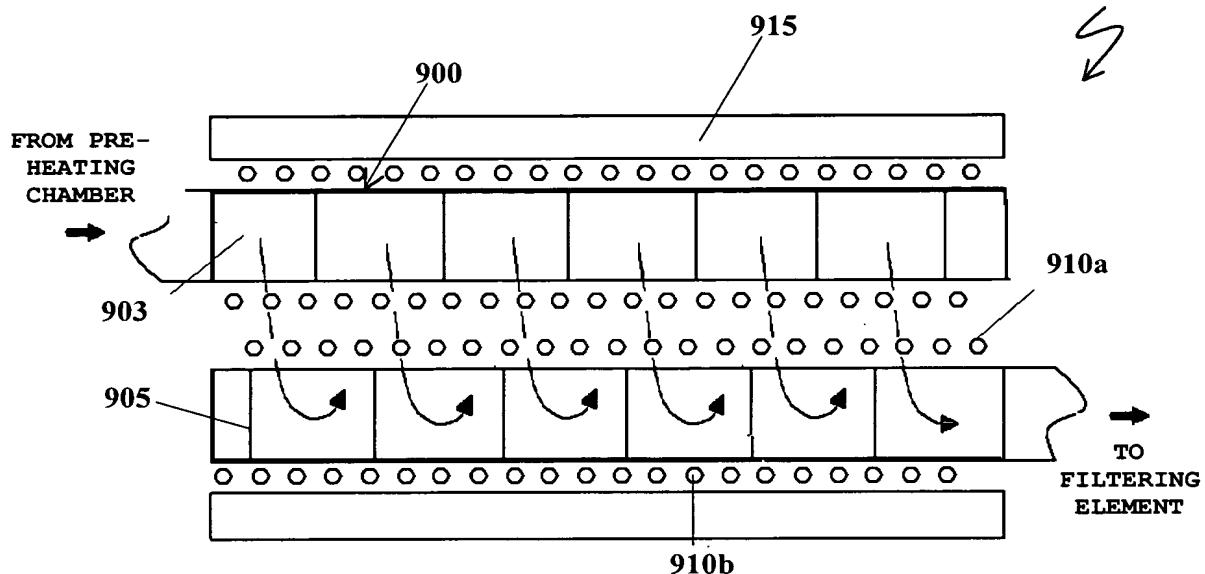
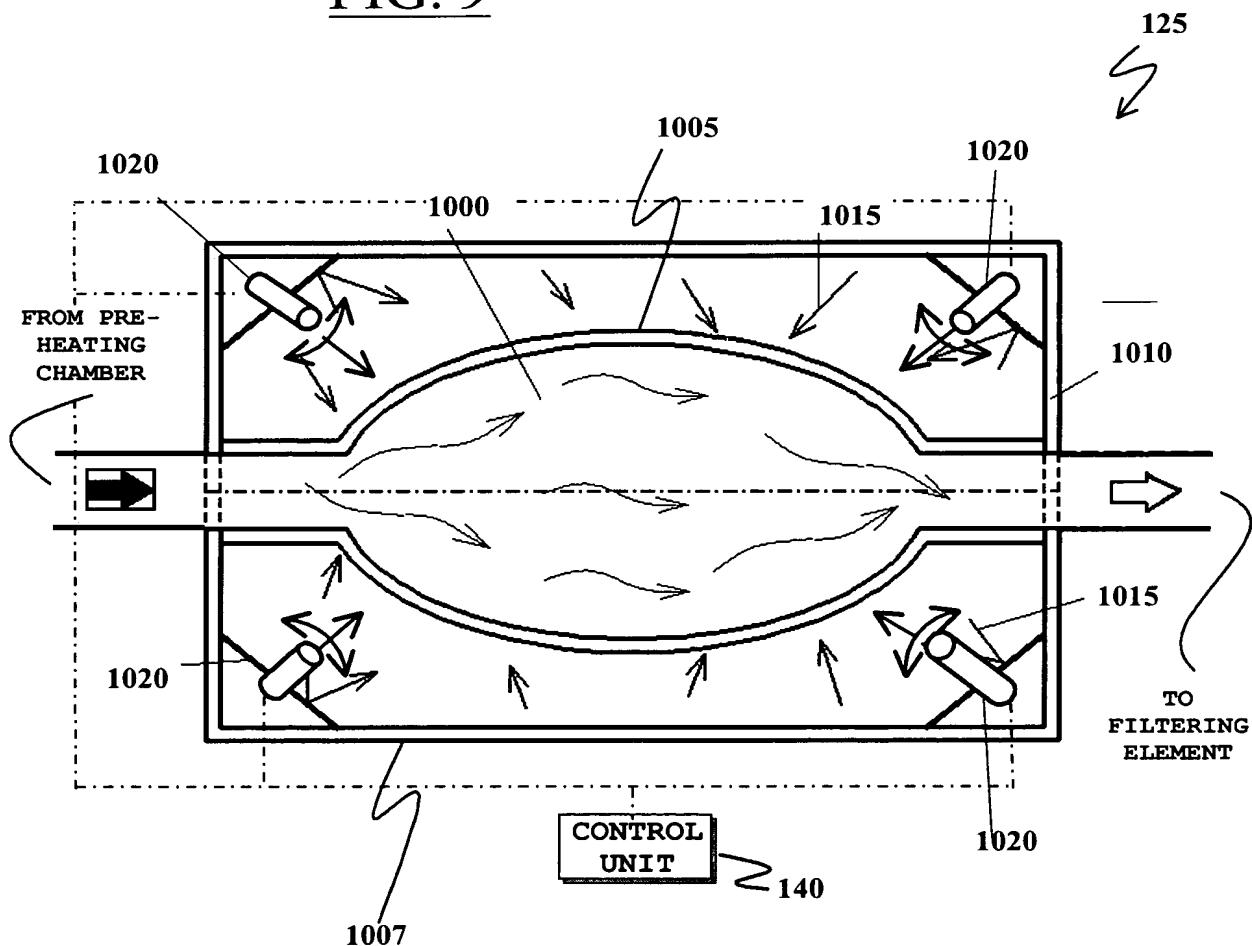
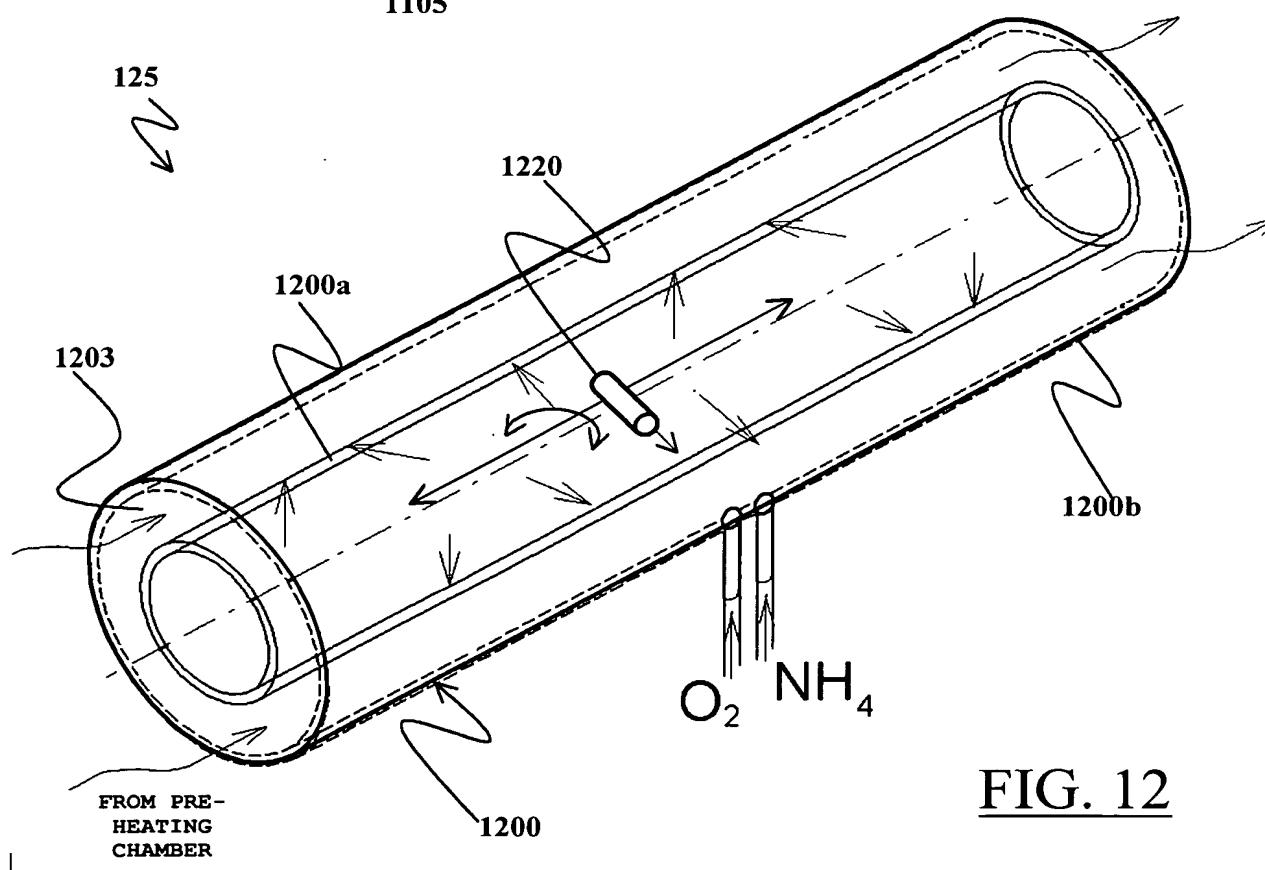
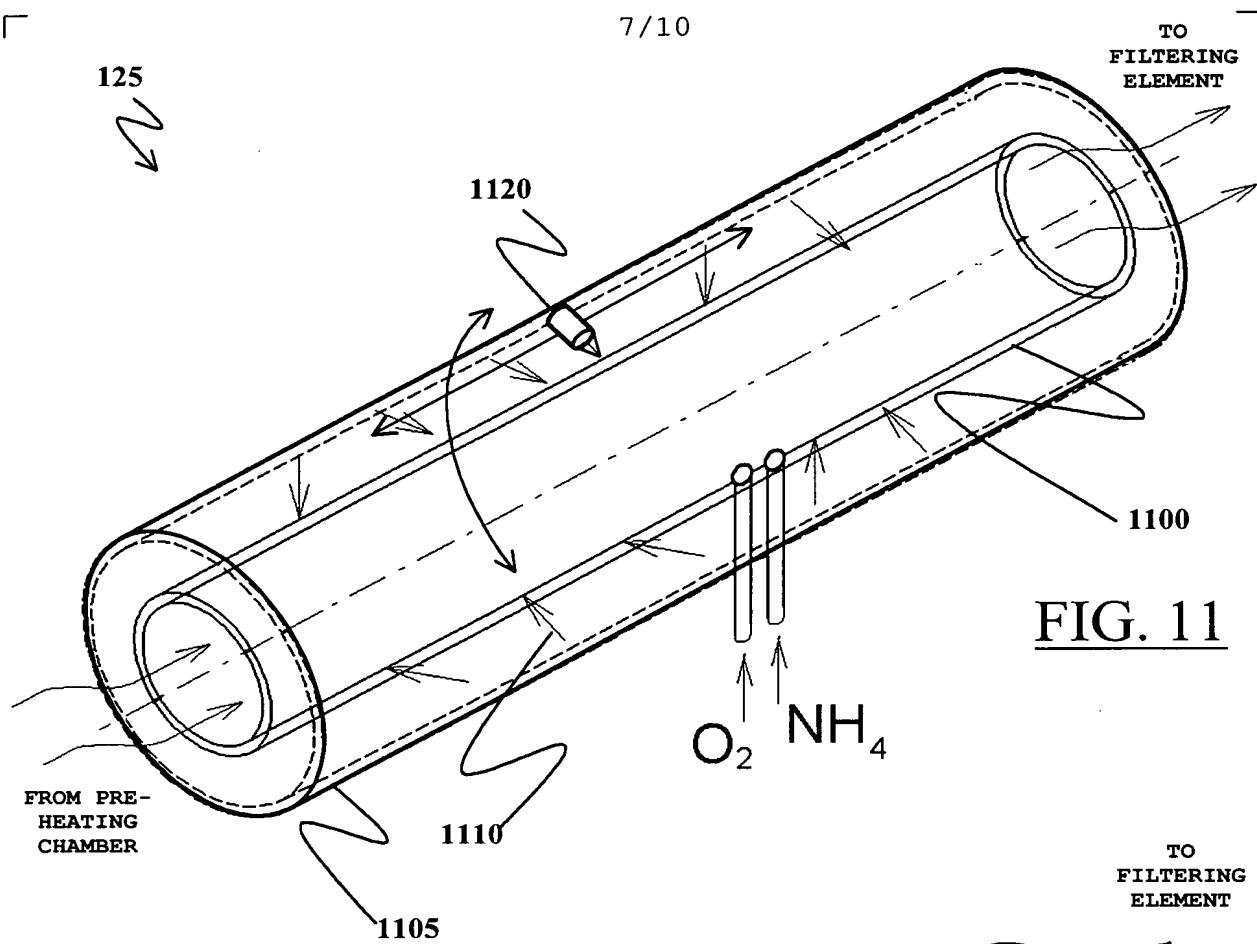
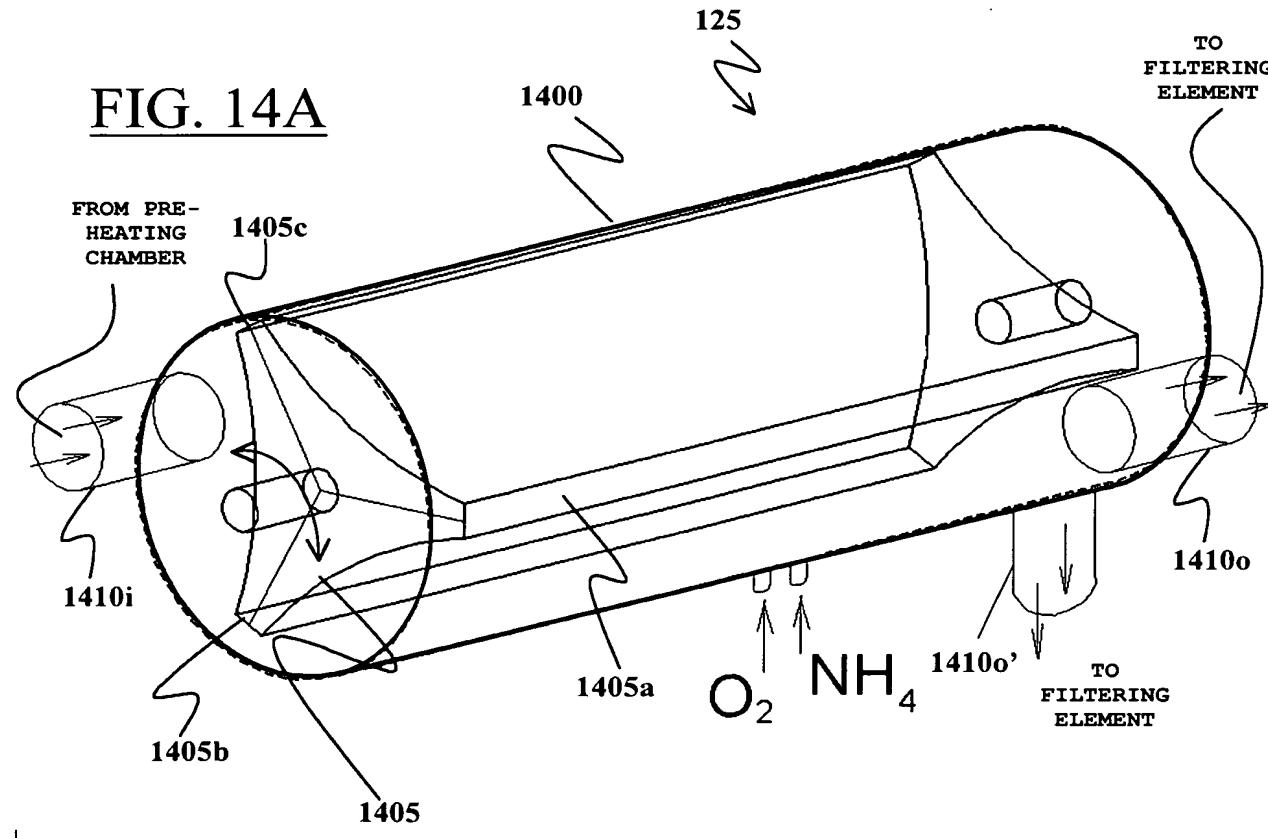
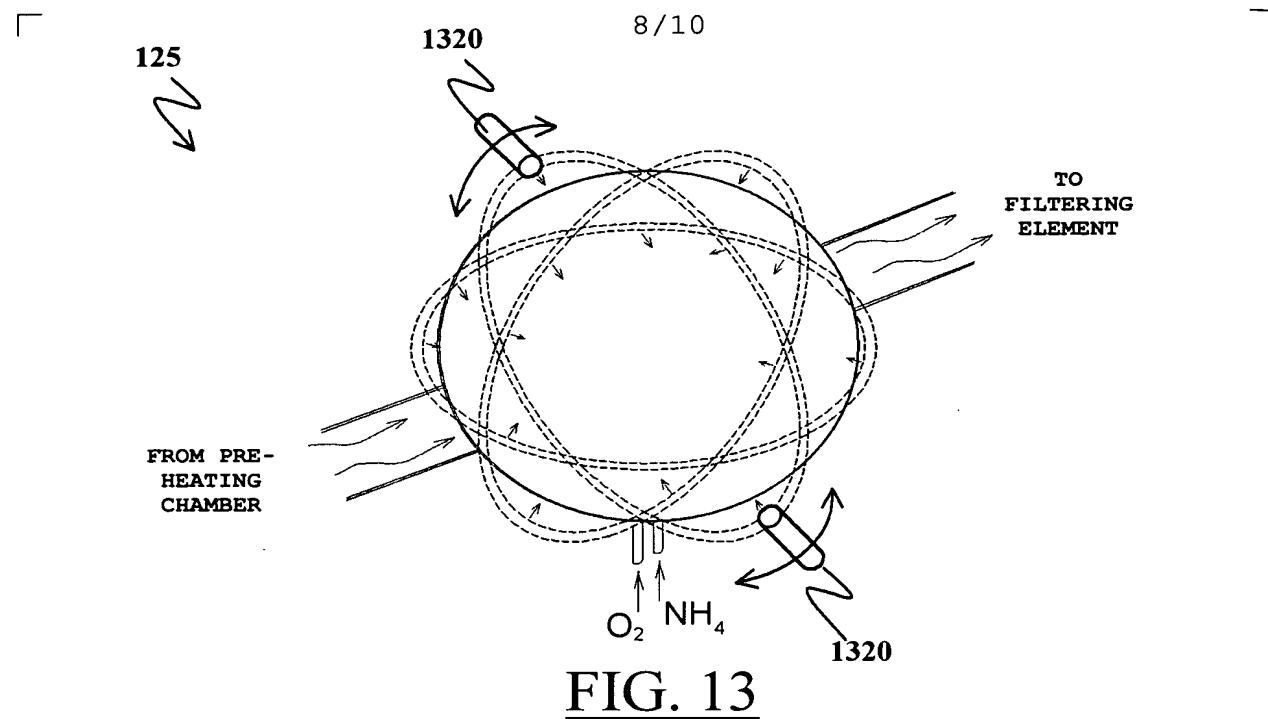


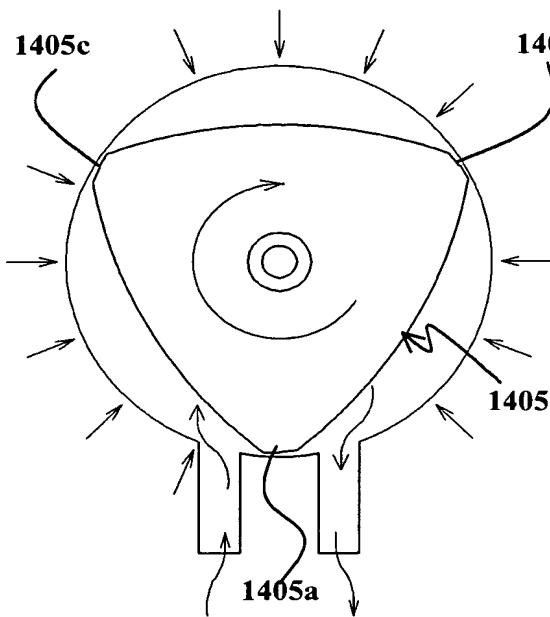
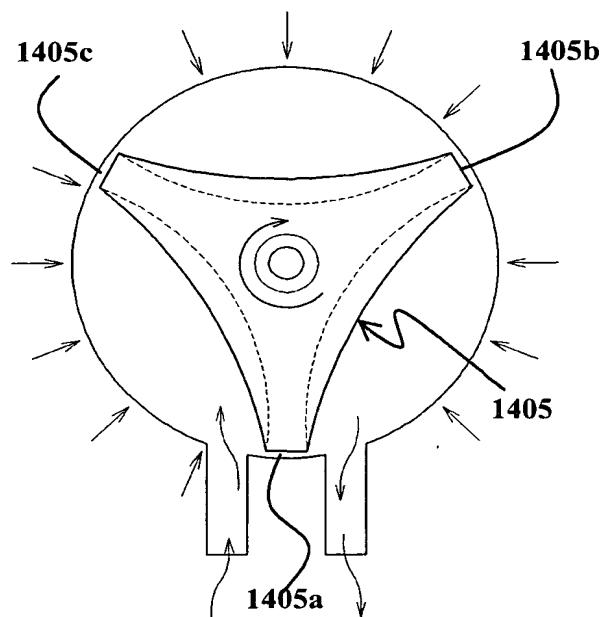
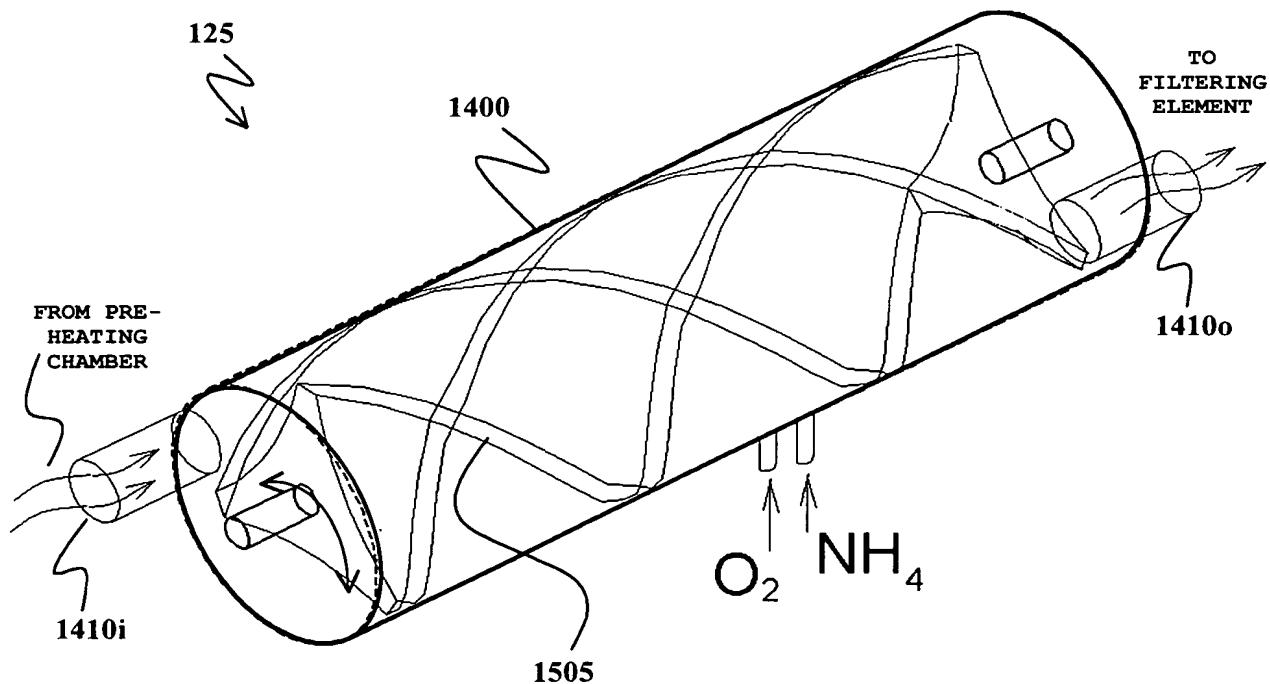
FIG. 9







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FIG. 14BFIG. 14CFIG. 15

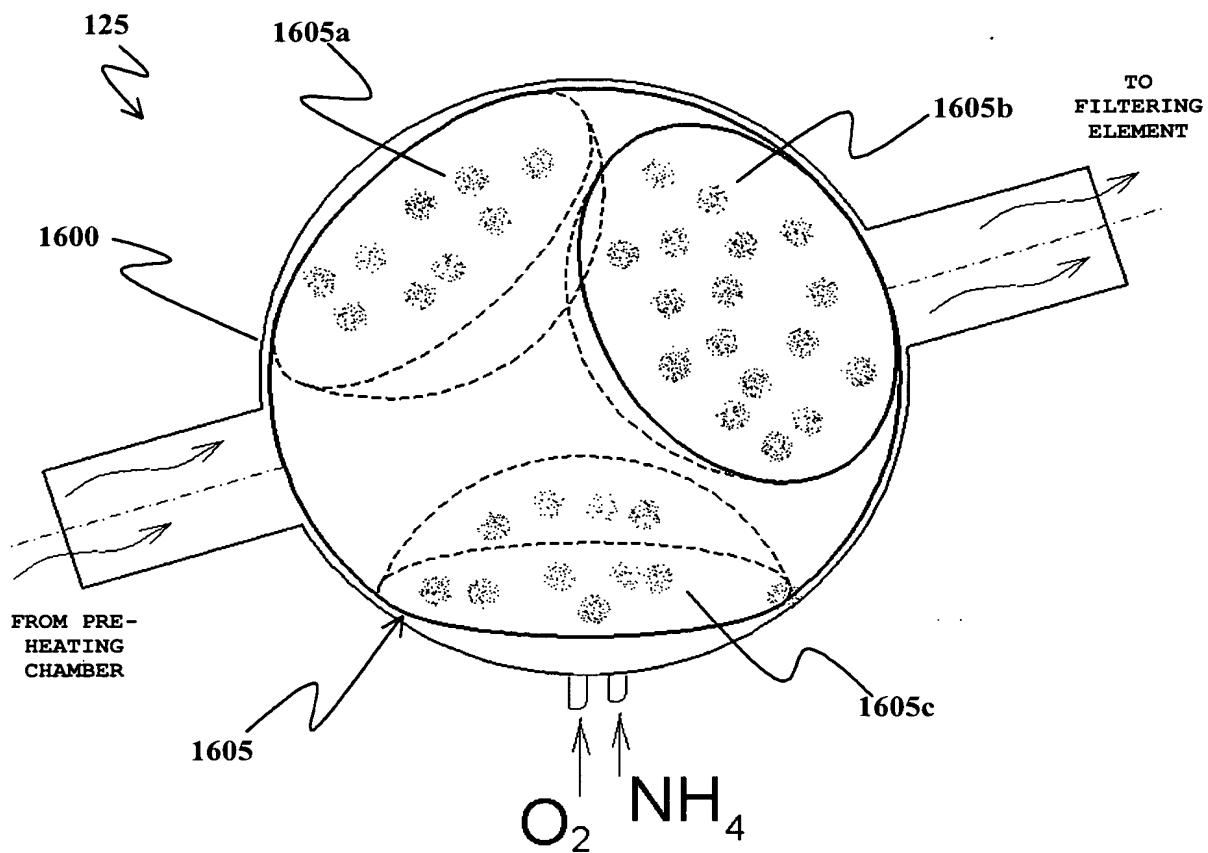


FIG. 16